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Yuankun Zhang

University of Wollongong, yz045@uowmail.edu.au

Shichao Ding

University of Wollongong, sdling@uow.edu.au

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Abstract

With the increasing applications of UHSS for the automotive industry, it becomes more and more important to develop a new forming technology as an alternative or even a replacement to roll forming to overcome the difficulties and problems of manufacturing the UHSS. With the increase of material's strength and decrease of its thickness, the springback of the material becomes more difficult to predict, which directly affects the application of roll forming in UHSS. Chain-die Forming, as an alternative to roll forming proposed and developed recently in Australia, is expected to be a solution to the problems addressed. It has been proved that Chain-die Forming has the advantages of low redundant strain components during forming and nearly zero residual stresses in products. In this paper, a special case of forming a UHSS U-channel with pre-made holes is studied in order to explore the limitations of Chain-die Forming and exhibit the advantages of the new method over roll forming. FEA is employed to simulate the forming process, and the results are compared with the experimental results.

Keywords

strength, ultrahigh, forming, die, chain, study, experimental, steel, uhss

Disciplines

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Experimental Study on Chain-die Forming for Ultrahigh Strength Steel (UHSS)

Yuankun Zhang, Shichao Ding*

Faculty of Engineering, University of Wollongong, Northfields, Wollongong, NSW 2500, Australia

With the increasing applications of UHSS for the automotive industry, it becomes more and more important to develop a new forming technology as an alternative or even a replacement to roll forming to overcome the difficulties and problems of manufacturing the UHSS. With the increase of material's strength and decrease of its thickness, the springback of the material becomes more difficult to predict, which directly affects the application of roll forming in UHSS. Chain-die Forming, as an alternative to roll forming proposed and developed recently in Australia, is expected to be a solution to the problems addressed. It has been proved that Chain-die Forming has the advantages of low redundant strain components during forming and nearly zero residual stresses in products. In this paper, a special case of forming a UHSS U-channel with pre-made holes is studied in order to explore the limitations of Chain-die Forming and exhibit the advantages of the new method over roll forming. FEA is employed to simulate the forming process, and the results are compared with the experimental results.

Keywords: Chain-die Forming, UHSS, residual stress, longitudinal strain, finite element analysis

1. INTRODUCTION¹

In today's society, Ultra-High Strength Steel (UHSS), or Advanced High Strength Steels (AHSS), is being widely introduced to the automotive industry in order to reduce the emission of CO₂ via reducing the costs of manufacturing and the weight of a motor vehicle. In manufacturing, reducing the CO₂ emission means that decreasing the total costs of a vehicle includes the steel used in a vehicle without scarifying the passengers' safety. On road reducing CO₂ emission means that driving a lighter vehicle consumes less fuel. UHSS is a favorite to automotive industry as its overall indexes are much higher than other materials. Troive and Ingvarsson concluded that roll forming UHSS has the advantages of reduced distortion compared to mild steel, smaller bend radius than bending and low capital cost.¹ In studying the process of roll forming UHSS, Lindgren also concluded that as the strength of deformable material increases, the deformation length increases and the peak

value and residual strain decrease.² However, in the current stage this type of material has the required strength, but very limited ductility. When the material's strength is over 800 MPa, some of the UHSS have an elongation of less than 15 %, which is much lower than that of IF and BH steels, leading to difficulties in applying those materials in manufacturing.

Roll forming has been widely appreciated by industries for mass manufacturing long and straight sheet metal products. However, the complexity of the deformation process has caused many fundamental and practical problems. The in-plane shearing leads to high transverse tension as the strip crosses the rolls, and the combination of bending, transverse tension and the doming of the strip can result in over-tension and the splitting of the strip as it comes into contact with the bend corner of rolls. Even in cases where the splitting does not occur, the transverse tension is still very difficult to predict and control, and the springback and residual stresses dominate the quality of the products.³ Although many studies were conducted to use "bending" to replace "stamping", and "flexible roll forming"

* Corresponding author, sding@uow.edu.au, Tel: +61-2-42215235

is also proposed to employ a computer system to control the positions and rotational angles of the forming rolls, the technology still has some fundamental difficulties, low efficiency and high cost.⁴ All these make it imperative to replace the conventional roll forming with a new forming approach.

Chain-die Forming, an alternative to roll forming, was proposed and developed recently in Australia to solve the problems addressed above. It was originally proposed to stretch the deformation length by increasing the virtual roll radii and employing discrete profiled die-blocks moving on a profiled track board to simulate the virtual large rolls.³ It is possible to achieve the goal of keeping the longitudinal strain and shear strain remaining within an acceptable level by controlling the deformation length, so that the causes of product defects in roll forming can be removed theoretically. The structure of a Chain-die Former has a pair of track boards which have very large radii with roller chains running on it, and also forming dies attached on the chains, as shown in Fig.1. The profiles of rolls are manipulated by the forming die-blocks mounted on the chains, and when a strip is fed into the forming space among die-blocks, the gap between the opposite die blocks is gradually reduced and the strip in the forming space is gradually bent to shape through a much longer forming distance than in roll forming.

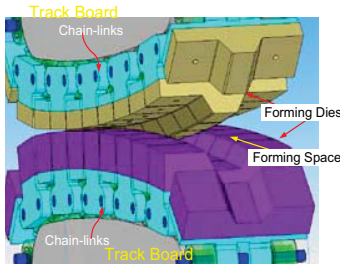


Fig. 1 The basic elements of Chain-die Forming

Preliminary studies proved that Chain-die Forming has the advantages of low redundant deformation during forming and nearly zero residual stresses in products. In this paper, this newly developed technology is further studied. As a special case to explore the limitations of Chain-die Forming and exhibit the advantages of the new method over roll forming, forming a UHSS U-channel with holes is studied. Experimental studies and FE simulation are conducted and discussed.

2. FEA MODELLING AND SIMULATION OF CHAIN-DIE FORMING

The Chain-die Forming process starts at the first contact between strip and dies, as shown in Fig.2 position (1) to fully complete the forming through the forming length, as shown in Fig.2(3). The tooling is similar as air-brake bending, and the top dies are designed similar to a punch die

and the bottom dies have a large radii corner to allow the flanges gradually bent up to a channel through the whole forming length.

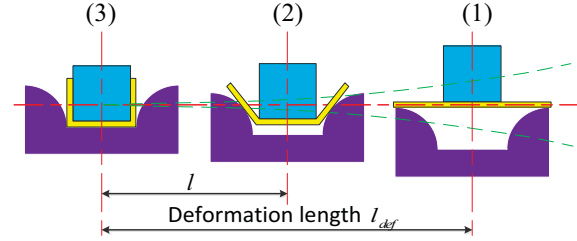


Fig. 2 The process of forming a 90° channel by Chain-die Forming

The blank's thickness is 0.5 mm and the width is 50 mm, and the deformed sample's shape is as shown in Fig.3, where the web is 20 mm wide and the flange is about 15 mm. The top dies radii at corner are 1 mm.

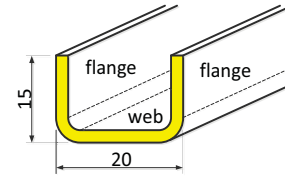


Fig. 3 Shape of final deformed sheet

The mechanical behavior of the sheet material used in the simulation and experiment is described by Swift's isotropic strain hardening law as also used in Heislitz *et al.*:⁵

$$\sigma_v = K(\varepsilon_0 + \varepsilon_p)^n$$

where σ_v is the flow stress; ε_p is the plastic strain, and the simulation parameters are summarized in Table I.

Table I. Summary of simulation parameters

Material model	Isotropic, elastic-plastic, strain hardening
Young's modulus E	210 GPa
Poisson's ratio ν	0.3
Strength coefficient K	617.2 MPa
Offset strain ε_0	0.001292
Strain-hardening exponent n	0.143
Sheet thickness t	0.5 mm
Sheet length L	300 mm
Friction coefficient μ	0.0
Roll property	Rigid

Due to the geometrical structural symmetry, only half of the geometry was modeled, as shown in Fig.4. The strip is illustrated with three interested positions following the sequence being formed of the starting, middle and final positions along the forming direction, named Head, Middle and Tail. The mesh consists of $(30 \times 50 \times 5)$ elements. The die rolls are assigned perfectly rigid and the working areas are treated as whole bodies without segmentation. The contact condition is set as frictionless for simplification. To validate the establish modeling, the die radii are setup to 51.5 mm to perform the simulation, and the results are quite close to the experimental results by Battacharyya.⁶

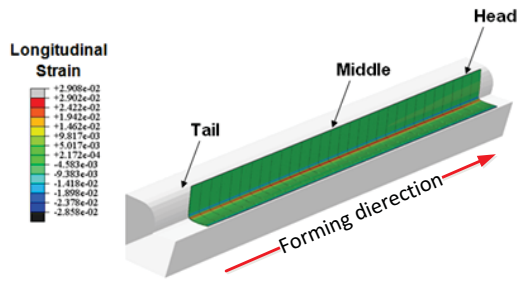


Fig. 4 Modelling of Chain-die Forming a U-profile channel

In this simulation, a relative motion between the strip and the rolls is applied to simulate the Chain-die Forming process for simplification and accuracy reasons. The two rolls are located with a cross sectional view as Fig.2(3), perpendicularly adjacent, 0.5 mm away (the strip thickness) and both set with longitudinal displacement for their forward motion. When the simulation starts, the two rolls move towards the strip simultaneously and the strip is gradually press-bent to the final profile when the top and bottom rolls are fully engaged. Fig.5 shows the final deformed shape obtained from ABAQUS FE simulation.



Fig. 5 Deformed shape from simulation

Close observation of the simulated shape shows that the web is not flat, but it does match with the shapes of produced samples. The difference about the flange is that the simulated flange is however not quite “flat” as shown in Fig. 6, but the samples do not have the problem and are nearly completely flat from visual observation.

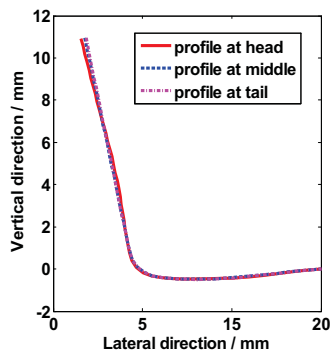


Fig. 6 Modelling of Chain-die Forming a U-profile channel

3. FEM SIMULATION RESULTS ANALYSIS

The development of longitudinal strains in which most roll forming engineers are interested is respectively measured at Head, Middle and Tail positions of 1.5 mm away from the strip edge, as shown in Fig.7. From the figure, the longitudinal strains at middle position are varying between -

0.04% and 0.03%. The strains at head and tail are even much smaller than at middle position within a range of $\pm 0.01\%$, as less constrains in axial direction at both ends. The head strains are larger than the tail because while the head strip starts deforming, the following strip gives resistance to the deforming head, and as the tail strip is to be deformed there is no following material to give resistance.

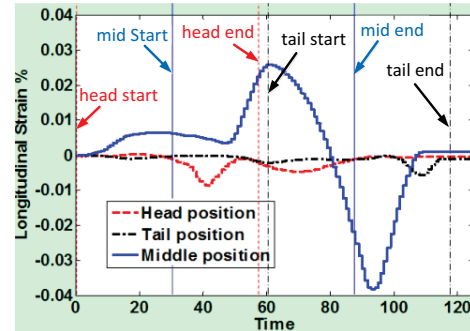


Fig. 7 Development of longitudinal strain

In the roll forming process, the width of the deformed flange is an important factor which affects the longitudinal strain distribution. In Chain-die Forming, this is also a key parameter which needs to be studied. Three flange width, 10, 15 and 20 mm are analyzed and the longitudinal strain developments during Chain-die Forming are plotted in Fig.8.

In Fig. 8 all longitudinal strains are in a very low state in elastic. To the head and tail, the flange width has a negative affection to the longitudinal strain and that can be explained as the wider flange increases the rigidity and in-plane shearing resistance, and leads to a smaller longitudinal strain as the width increases. In the middle position, as shown in Fig.8(b) the stress state experiences a tension in the first half of the forming process and then changes to compression. The maximum tensile strain has a positive relationship with the flange width, but the compression strain does not follow this trend. For the cases of 10 and 15 mm, the peak compression strains are nearly same, but as the flange width increases to 20 mm, the peak value drops. This phenomenon can be understood as the compression stress is applied on the flange, while the flange width is smaller, the resistance against wrinkling is higher, and the deformation is along the axis of the press force and strip is just simply compressed without wrinkling. While the flange is wide enough, the compressive force makes the edge wrinkle, and the strip is more likely to vary to a wavy shape along the edge to release the compressive stresses and that results in a lower compressive strain than the case of 20 mm flange width. It should be pointed out that all the longitudinal strains are in elastic, after forming these stains are fully springback as declaimed advantages of the new method, and if the longitudinal strain is larger than the elastic limitation, we can always either break down the forming from one to two or increase the forming length via increase of the roll radii.

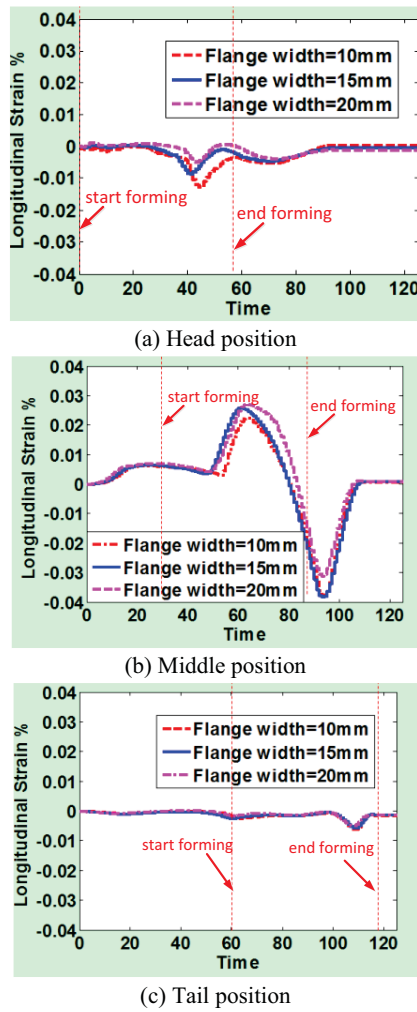


Fig. 8 Strain comparison for different flange widths

Another key parameter roll forming engineers may be interested in is the relationship between longitudinal strain and bend angle. Fig.9 shows the FEA analysis results and it can be observed that at the head and tail the strain is extremely small, but in the middle position it is very clear that with the increment of bend angle, the peak longitudinal strain increases.

4. EXPERIMENTAL STUDIES

The experimental work was processed on the prototype Chian-die Former built to demonstrate the working principle, as shown in Fig.10(a). The shapes of the dies are also shown in Fig.10(b). It should be addressed that the dies used in these tests were designed to form a right angled channel section in one pass, an un-achievable target to roll forming, to reveal the potential advantages over roll forming. Also it needs to be mentioned that even the original design had a pair of gear-motors to drive the top and bottom chains individually, but in this group of tests there was only a 90 W single phase AC motor with a speed controller used to drive the prototype.

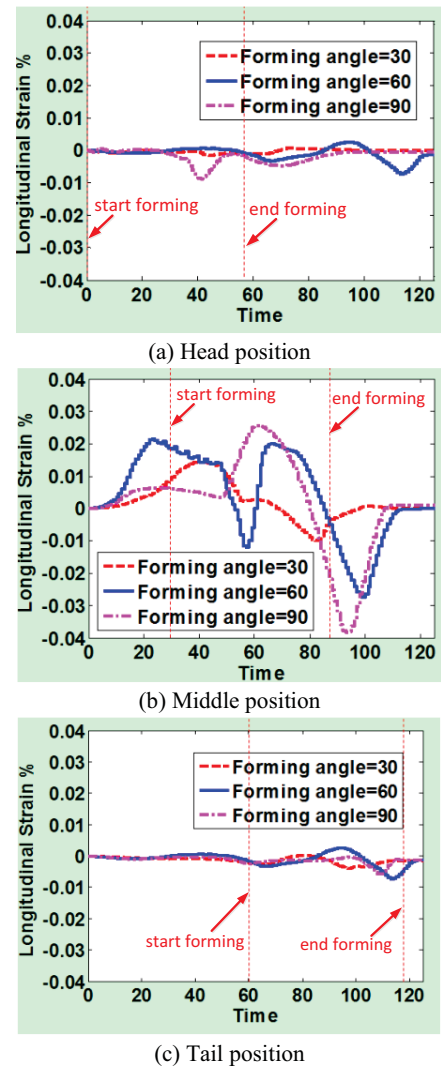
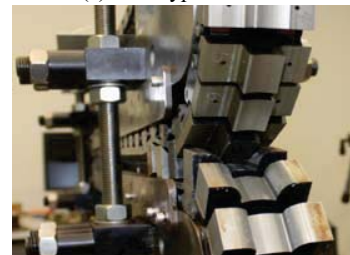


Fig. 9 Strain comparison for different forming angles



(a) Prototype machine



(b) Assembly of die-blocks

Fig. 10 Prototype machine and die-blocks

The samples used in this experiment were 0.425 mm base metal thickness G550 steel, and were first blanked to a size of 45 mm in width and 200 mm long as limitation of the dies. The G550 has a tensile strength about 700MPa, which is similar to a DP steel in strength. In roll forming tooling design, there are some restrictions like avoiding holes too close to the edge or bend, or cross the bending line. In those samples, however, holes are punched at different positions, which are close to the edge or bend (1 mm), across the bend and multiple positions. Samples produced are shown in Fig.11.

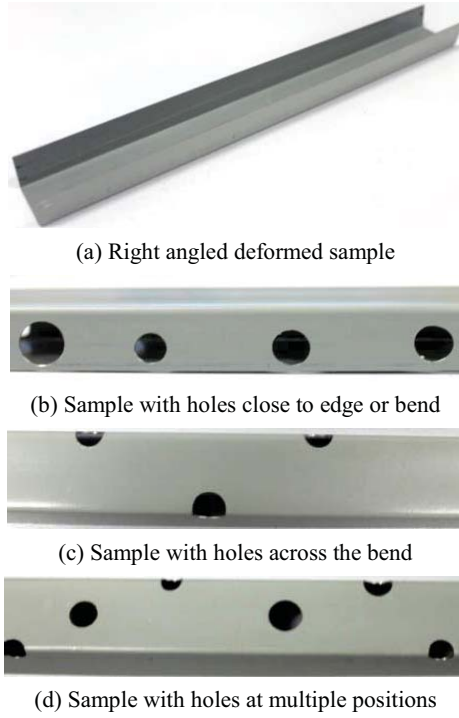


Fig. 11 Deformed samples with holes

Fig.12 shows a blank with different punched holes on the flange and the channel after forming. From observation and manually checking, the deformed sample is nearly right angled, and there is no visible surface damage on the sample and the surface is smooth. There are no product defects found in the formed products such as end flares, edge waves, longitudinal curvature and twisting, which shows that the residual stresses are well eliminated and controlled. Besides, there is no imperfection around the pre-punched holes, and that is another evidence that the redundant deformation is well controlled and the residual stresses are thoroughly eliminated.

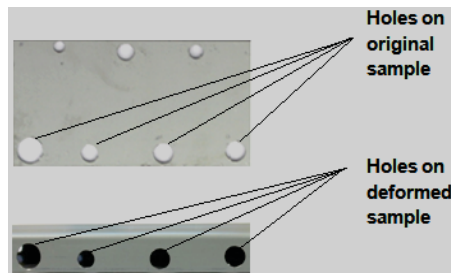


Fig. 12 Sample profile comparison before and after deformation

In the strain gauge measurement, the data acquisition system employed is the NI cDAQ-9172 with a NI 9237 simultaneous bridge module. The strain gauges used in this study is ECH-120-2AA-11-RL30 from BCM. The strain gauge is 120 ohm and 2×2 mm in size with long legs. The strain gauges were bonded onto both top and bottom surfaces of the strips at Head, Middle and Tail positions respectively. The average of the recorded longitudinal surface strains on the two surfaces were calculated and plotted as the longitudinal membrane strains, and are shown in Fig.13. From the figure, the longitudinal strains at the three various positions were vibrating at a lower level of 0.03% , which is similar with the FEA simulation results.

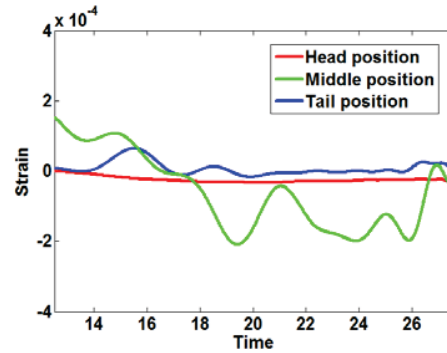


Fig. 13 Experimental longitudinal strain measured at different positions

The experimental results were then compared with FEA results. Fig.5 shows the shape predicted by FEA simulation and it well represented the actual shape of the sample produced on prototype, as shown in Fig.14. The longitudinal strains are also compared and are shown in Fig.15. From the figure, the strain developments were both within a very small range of $\pm 0.04\%$, which proves both FEA simulation and strain gauge measurement show that redundant strains are very small and results in the residual stresses of zero after forming.

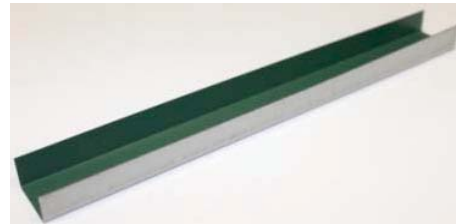


Fig. 14 Actual product by Chain-die Forming

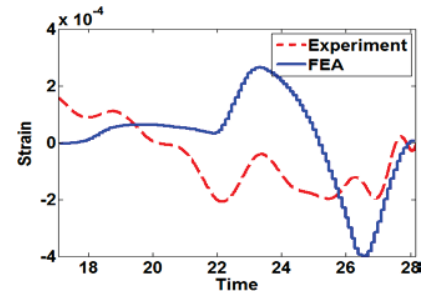


Fig. 15 Comparison of Experimental and FEA results

It should be pointed out that because both of the FEA simulation and strain gauge measurement showing the longitudinal strains are in a very low level, the comparison with those two results to find some common characteristics does not make any sense as during the strain gauge measurement any machine's vibration from transmission system or chain/die's motion will cause the strip's shape variation during forming and that will affect the accuracy of the measurement.

5. CONCLUDING REMARKS

As a newly developed forming technology, Chain-die Forming shows the advantages of lower redundant strains during forming and nearly zero residual stresses in products. Also, through analyzing the forming process and forming the samples that are difficult to be roll formed, the results prove that due to the low redundant deformation, some unachievable targets can be completed by the new forming method. This paper has presented a bright future for the sheet metal forming industry and has been especially important to UHSS. The low redundant deformation means even a low formability UHSS can still be used to form a complex shape product. Some concluding remarks from the studies introduced can be summarized:

- 1) It is possible to use Chain-die Forming to form a UHSS right-angled U-channel section in one pass. As there is very low longitudinal strain on the flange and web, the forming process does not stretch the pre-punched holes on the flanges and web even the holes are very close to the edges or bends and across the bends. Some limitations in roll forming tooling design are no longer applied to Chain-die Forming tooling design. Also, as the UHSS U-channel formed does not have any strain-hardening on the flanges, the channel can be used to further process such as bending;
- 2) To Chain-die Forming a channel section, the maximum longitudinal strain occurs at the edge of flange on the middle position. The flange width is positive to the tensile longitudinal strain but negative to the compressive longitudinal strain;
- 3) The achievement of forming right-angled U-channel in one pass by Chain-die Forming proves that Chain-die Forming has great capability and productivity in UHSS forming as the springback is a negligible factor in UHSS forming tooling design. A much shorter production line than a roll forming line is expected as there is no need of correction stands;
- 4) Both FEA simulation and strain gauge measurement show that redundant strains are very small and the residual stresses are zero after forming;
- 5) Even the final profile is still not perfectly right-angled after springback, further studies need to be carried out to predict the shape accurately to minimize the tolerance. In industrial application, a computer controlled roll forming pass to correct the forming angle is necessary and that needs to be further studied.

There is still a lot of work to be done before the first real part is produced for industry. The acceleration of this process requires lots of people's efforts and also supports from governments and industry.

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